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# Extragalactic Astronomical Masers I

## - A tool for exploring the innermost part of active galactic nuclei

Yoshiaki Hagiwara

### Abstract

Maser is an acronym of Microwave Amplification by Stimulated Emission of Radiation. Maser emission is seen in astrophysical environments like starforming sites, evolved stars in our Galaxy, and those in external galaxies. Molecules of hydroxyl (OH), methanol (CH<sub>3</sub>OH), water (H<sub>2</sub>O), and silicon monoxide (SiO) are typically observed as masers in these objects and they emit intense emission in the interstellar space under ultimate physical conditions. It is also known that OH and H<sub>2</sub>O masers are observed in distant external galaxies, as well as in our Galaxy. These extragalactic masers are observed very luminous and compact. Observational studies using Very Long Baseline Interferometry (VLBI) have shown that extragalactic masers are powerful tools for understanding the activity and dynamics within central few parsecs of galaxies hosting active nuclei. Here I review the current studies of extragalactic masers and future prospects, including the most recent research of extragalactic water maser emission found at submillimeter wavelength in nearby active galaxies. These masers could probe dense molecular material closest to the central engine of galaxies.

**Keywords :** Interstellar medium, molecular gas, maser, active galaxies, galactic nuclei

## 1 Introduction

Maser (Microwave Amplification by Stimulated Emission of Radiation) is a radio wave equivalent of laser at optical wavelength. Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. Laser is an artificial light and it is very different from other lights in that a laser light is highly collimated and coherently emits in space. Similarly, maser emits very narrow and intense emission at microwave or radio wavelengths over long distances. Thus, sources of maser emit collimated emission. Astronomical maser naturally occurs in newly formed stars and evolved stars under peculiar physical conditions (e.g., Elitzur 1992). The maser is produced by population inversion occurring between the two different energy levels, which are the ground and upper states. The mechanism leading to the population inversion is the pump. Maser pumping is thus caused by the transitions of molecules between the two different energy levels. The mechanism that causes maser pumping is thought to be either collision or external radiation (e.g., Elitzur 1992).

Maser emits very intense radiation that we can see the maser emission occurring in distant galaxies typically up to  $\sim 10^2$  Mpc as well as in our Galaxy. Very Long Baseline Interferometry (VLBI) with the angular resolution of less than 0.001 arcsecond is one of the most important tools for the study of the angular structure, distribution, and kinematics of compact maser emission. VLBI observations have proved that extragalactic masers are powerful tools for understanding the activity and dynamics within central few parsecs of active galaxies.

In this article, the current status of studies of extragalactic masers is briefly reviewed by focusing on H<sub>2</sub>O masers.

## 2 Masers

Since hydroxyl (OH) maser was discovered as the first astronomical maser in H<sub>II</sub> regions in our Galaxy in 1965 (Weaver et al. 1965), methanol (CH<sub>3</sub>OH), water (H<sub>2</sub>O), silicon monoxide (SiO), and other species of maser had been identified one after another both in Galactic and extragalactic objects. In general, many of these masers are found associated with starforming activity or envelope of late type stars, however OH, H<sub>2</sub>O, and HCHO (formaldehyde) masers are also observed in external galaxies beyond the Large Magellanic Clouds (LMC). Recently, CH<sub>3</sub>OH maser has been detected in the starforming galaxy, M31, one of the galaxies in the Local Group (Sjouwerman et al. 2010). However, there has been detected no other extragalactic CH<sub>3</sub>OH maser at this time in late 2015. Properties of astronomical masers are 1) isotropic luminosity of masers is about six orders of magnitude larger than that of stellar masers, while the emitting region is only about one astronomical unit ( $\approx 1.5 \times 10^{13}$  cm), very compact (Thus, the maser emitting region is called a maser spot.), 2) line-widths of spectrum are very narrow, and 3) the strength of intensity is enormous and variable in time. These properties are common both in Galactic and most of extragalactic masers. Regarding to 1), the extragalactic masers with such large luminosity are called *megamaser*.

## 3 VLBI and masers

VLBI provides an angular resolution of less than 0.5 milliarcsecond at 22.2 GHz (e.g., Thompson et al. 1986), which corresponds to the frequency of the H<sub>2</sub>O maser emission. Imaging of each maser spot using VLBI enables to reveal the angular geometry of the maser on scales of 0.1-1 parsec for nearby galaxies at a distance of 5-50 Mpc. There is no doubt that VLBI is an important tool for studying the angular distribution of maser spots in the active galaxies.

#### 4 Extragalactic Masers

Table 1 displays a summary of extragalactic masers. It is clear that HCHO and CH<sub>3</sub>OH masers are not yet well studied in extragalactic objects. The discovery of a 6.7 GHz CH<sub>3</sub>OH maser in the 10 kpc molecular ring of M31, the Andromeda galaxy was reported, and the luminosity is similar to that of Galactic masers (Sjouwerman et al. 2010). It is interesting to note that extragalactic OH and H<sub>2</sub>O masers differ from Galactic masers in that their isotropic luminosity ( $L_{\text{iso}}$ ), assuming that the maser radiation emits isotropically by two or three orders of magnitude larger than that of the Galactic masers. The luminosity of the Galactic masers ranges typically from 0.001—0.01  $L_{\odot}$ . The strongest H<sub>2</sub>O maser of the W49N region in our Galaxy has the luminosity of  $\sim 1 L_{\odot}$ . These masers with large luminosity are categorized to megamaser. Both OH and H<sub>2</sub>O megamasers are known in distant galaxies. It should be noted that the properties between OH and H<sub>2</sub>O megamasers are quite different (see Table 1). The line-widths and spacial distribution of OH megamasers are different from those of H<sub>2</sub>O megamasers: H<sub>2</sub>O megamasers pin-point locations of molecular gas with limited velocity range, suggesting that they trace kinematics of molecular gas on scales of parsecs in the nuclear regions of active galaxies.

#### 5 OH Megamasers

There have been known two types of OH megamasers (OHMMs); they are OH kilomaser and megamaser. The former has luminosity of up to  $\sim 10^3 L_{\odot}$  and the latter does more than  $10^6 L_{\odot}$ . Most of OHMMs are found in the transitions of 1665 and 1667 MHz. Some OH megamasers are observed in other transitions. The total number of the extragalactic OH maser including OH kilomaser is about 100. The mechanism that excites OHMM is thought to be the infrared-pumping with large infrared radiation in infrared galaxies (e.g., Baan 1989). These

**Table 1: A summary of extragalactic masers**

Molecule	H <sub>2</sub> CO	OH	CH <sub>3</sub> OH	H <sub>2</sub> O	H <sub>2</sub> O
	Formaldehyde	Hydroxyl	Methanol	Water	Water
Proto type	Arp220 <sup>1</sup>	Arp220 <sup>2</sup>	M31 <sup>3</sup>	M33 <sup>4</sup>	NGC4945 <sup>5</sup>
Host galaxy	ULIRG <sup>a</sup>	ULIRG, SB <sup>b</sup>	SF <sup>c</sup>	SF <sup>c</sup>	AGN <sup>d</sup>
The approximate total number of detection	5	100	1	15	150
Frequency (GHz)	4.829	1.667/1.665	6.66	22.2	22.2
Distance (Mpc)	50-100	50-1000	0.7	0.7-10	5-100
Luminosity (L <sub>☉</sub> )	100	100-10 <sup>4</sup>	<1	0.001-1	10-10 <sup>4</sup>
Spectral line-width (km s <sup>-1</sup> )	50–100	50–100	5	< 2-3	< 2-3
Scales of spacial distribution (parsec)	-	10-100	-	<10	<1

1. Baan et al. 1986; 2. Baan et al. 1982; 3. Sjouwerman et al. 2010; 4. Churchwell et al. 1977; 5. Dos Santos et al. 1979

a: Ultra Luminous Infrared Galaxies

b: Starburst galaxies

c: Starforming galaxies

d: Active Galactic Nuclei

infrared-luminous galaxies are classified to ULIRG (Ultra Luminous Infrared Galaxies). Interestingly, ULIRG have double galactic nuclei in their center with notion that these nuclei are in the process of galaxy-galaxy merger, colliding, or interaction, which triggers starburst-activity inside the galaxies (Sanders et al. 1988).

## 6 H<sub>2</sub>O Megamasers

Extragalactic H<sub>2</sub>O masers can be categorized according to their luminosity. Masers having large luminosity ( $L_{\text{iso}} > 10$  solar luminosity ( $L_{\odot}$ )) are associated with active galactic nuclei (AGN). They are known as H<sub>2</sub>O megamasers.

Low-luminosity ( $L_{\text{iso}} < 10 L_{\odot}$ ) H<sub>2</sub>O masers are mostly associated with star-forming activity (Greenhill et al. 1993), however some of them are considered to

be in low radio luminosity AGNs (e.g., Ho et al. 1987, Hagiwara 2007). There has been an open question whether or not these low-luminosity masers are associated with AGN-activity.

The luminosities of Galactic H<sub>2</sub>O masers that are commonly observed in the envelopes of evolved stars and starforming regions range from 0.001 L<sub>⊙</sub> to 1 L<sub>⊙</sub>, typically. H<sub>2</sub>O maser with a luminosity well above 1 L<sub>⊙</sub> has never been found in our Galaxy.

H<sub>2</sub>O masers observed in nearby starforming or starburst galaxies with L<sub>iso</sub> values of 0.01–1 solar luminosity (Churchwell et al. 1977, Hagiwara 2007) are most likely to originate from starforming activity in host galaxies. On the other hand, the sub-population of H<sub>2</sub>O masers with  $1 L_{\odot} < L_{\text{iso}} < 10 L_{\odot}$  is known, most of them are considered to arise in starforming sites in galaxies, while some are in AGN like megamasers. The main reason of the low-luminosity is probably due to close to a face-on view of torus structure around the nucleus in the line of sight, or misalignment between the disk and a nuclear continuum in the line of sight (Hagiwara et al. 2003). This supports the fact that the low-luminosity masers in Type 1 Seyfert nuclei have an obscuring structure by a close face-on view (e.g., Braatz et al. 2003, 2004, Hagiwara 2007).

Figure 1 explains the inner structure of a nuclear region of AGN (e.g., Antonucci and Miller 1985); one can see that water molecules are abundant in the obscuring medium surrounding a central engine of a galaxy and strong radiation from a central engine yields the condition giving a rise to the excitation of maser. So, we can see the maser if the edge-on configuration in figure 1 is aligned to the line of sight.

The maser emission consists of components near or at the systemic velocity of a galaxy and Doppler-shifted components spread over 200–300 km s<sup>-1</sup> or

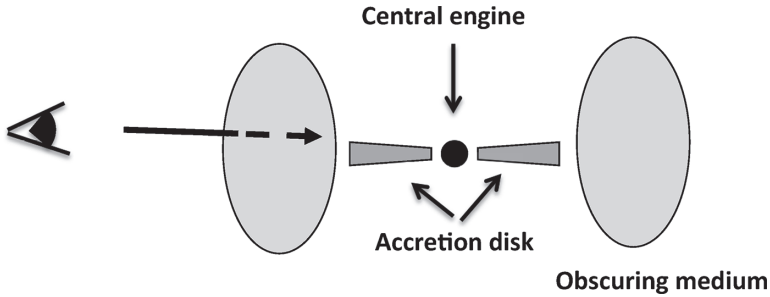


Fig. 1: A schematic view of the inner part of active galactic nuclei (AGN) (Antonucci and Miller 1985), which consists of a central engine of a galaxy, an accretion disk, and an obscuring medium surrounding the nuclear region.  $\text{H}_2\text{O}$  megamaser emission can be observed if the maser disk or torus where  $\text{H}_2\text{O}$  molecules are abundant is seen edge-on view to the line of sight. The  $\text{H}_2\text{O}$  megamaser (nuclear maser) is likely to be detected toward narrow-line AGN such as LINER or Type 2 Seyfert galaxies in which surrounding materials like a molecular disk or torus are aligned between the nucleus and observers (the earth).

even higher on either side of the systemic velocity (Figure 2). These Doppler-shifted components that are highly blue- or red-shifted are called high-velocity components. The high-velocity components were originally identified toward the LINER galaxy NGC 4258 (Nakai et al. 1993), and the total velocity spans of the galaxy are  $\pm \sim 1,000 \text{ km s}^{-1}$  with respect to the systemic. Such high-velocity emission was detected in some other AGN (Moran et al. 1999, Greenhill et al. 2009). At this time of 2015, more than 160 extragalactic  $\text{H}_2\text{O}$  masers have been detected (e.g., Braatz et al. 2004, Kondratko et al. 2006), majority of which are megamasers. They have been detected exclusively toward narrow-line AGN, where a molecular gas disk or torus obscures a central engine of a galaxy in the line of sight. Extragalactic  $\text{H}_2\text{O}$  masers outside AGN are also known (see Table 1) in starforming galaxies. As explained in this and earlier sections, the  $\text{H}_2\text{O}$  megamasers show very different characters compared with other extragalactic masers.  $\text{H}_2\text{O}$  megamasers can probe the innermost part of AGN in terms of geometrical distribution and kinematics of maser spots. In this sense,  $\text{H}_2\text{O}$



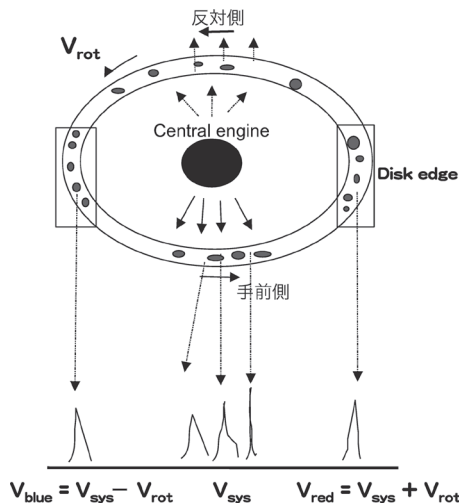


Fig. 2: A cartoon model of the  $\text{H}_2\text{O}$  maser disk in the central few parsecs of AGN. Using this model, Doppler-shifted components of maser emission that originates from a rotating disk can be explained.  $V_{\text{sys}}$ ,  $V_{\text{rot}}$ ,  $V_{\text{red}}$ , and  $V_{\text{blue}}$  denote a systemic velocity of a galaxy, rotation velocity of the disk, red-shifted velocity, and blue-shifted velocity, respectively. The maser excitation occurs in the line of sight. The blue-shifted emission is seen toward the approaching side of the disk, while the red-shifted emission is seen in the farther side of the disk. The maser on both side of the disk-edge is seen enhanced due to longer gain path in the line of sight. The strongest maser emission near the systemic velocity amplifies background radio continuum radiation from a central engine.

megamasers that associate with AGN-activity in nuclear regions of AGN are called nuclear maser. The distances to galaxies harboring nuclear masers are measured by analysis of proper motions and accelerations of maser components at galaxy's systemic velocity, assuming simple geometric calculation (e.g., Moran et al. 1999).

## 7 Summary

Astronomical masers are observed both in starforming sites in the Milkyway Galaxy and near active galactic nuclei in external galaxies. Observations of the

nuclear H<sub>2</sub>O maser coupled with VLBI imaging at the milliarcsecond angular resolution have enabled to reveal the spatial distribution of the maser and gas kinematics associated with the AGN-activity by its velocity structure. It has been recognized that H<sub>2</sub>O maser can provide information of the inner few parsecs of galactic nuclei, closer to the central engine.

When OH maser was first discovered in 1965, no one might not be able to imagine that the maser would become such an important tool in investigating the inner structure of active galactic nuclei. It seems to be difficult to completely understand the pumping mechanism of the masers, however we can utilize masers simply as a probe for the gas kinematics of galactic nuclei and their environments.

Recent studies of sub-millimeter extragalactic masers will be reviewed in the paper II.

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